## Phenomenological Analogies in Black Hole Systems of all Masses

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I review the progress made on the physics of relativistic jets from black hole systems in the context of the analogy between AGN and microquasars that was proposed one decade ago. If the emerging empirical correlations between the observational properties of stellar and supermassive black holes will become more robust, we will use them to determine the mass and spin of black holes, independently of theoretical models. Microquasars are fossils of sources of Gamma-ray bursts (GRBs) of long duration, and their kinematics provides observational clues on the physics of collapsars. If jets in GRBs, microquasars and AGN are due to a unique universal magnetohydrodynamic mechanism, synergy between the research on these three different classes of cosmic objects will lead to further progress in black hole physics and astrophysics.

### §1. Physics in black holes of all mass scales

The physics in all systems dominated by black holes is essentially the same, and it is governed by the same scaling laws. The main differences derive from the fact that the scales of length and time of the phenomena are proportional to the mass of the black hole. If the lengths, masses, accretion rates, and luminosities are expressed in units such as the gravitational radius ( $R_q = 2GM/c^2$ ), the solar mass, and the Eddington luminosity, the same physical laws apply to stellar-mass and supermassive black holes.<sup>1),2)</sup> For a black hole of mass M the density and mean temperature in the accretion flow scale with  $M^{-1}$  and  $M^{-1/4}$ , respectively. For a given critical accretion rate, the bolometric luminosity and length of relativistic jets are proportional to the mass of the black hole. The maximum magnetic field at a given radius in a radiation dominated accretion disk scales with  $M^{-1/2}$ , which implies that in the vicinity of stellar-mass black holes the magnetic fields may be 10<sup>4</sup> times stronger than in the vecinity of supermassive black holes.<sup>1)</sup> In this context, it was proposed<sup>3),4)</sup> that supermassive black holes in quasars and stellar-mass black holes in x-ray binaries should exhibit analogous phenomena. Based on this physical analogy, the word "microquasar" was chosen to designate compact x-ray binaries that are sources of relativistic jets (see Figure 1).

### §2. Superluminal motions in AGN and microguasars

A galactic superluminal ejection was observed for first time in the black hole x-ray binary GRS 1915+105, at the time of a sudden drop in the BATSE 20-100 keV flux.<sup>5)</sup> Since then, relativistic jets with comparable bulk Lorentz factors  $\Gamma = 1/[(1-\beta)^2)]^{1/2}$  as in quasars have been observed in several other x-ray binaries.<sup>6)-8)</sup> At present, it is believed that all x-ray accreting black hole binaries are jet sources.

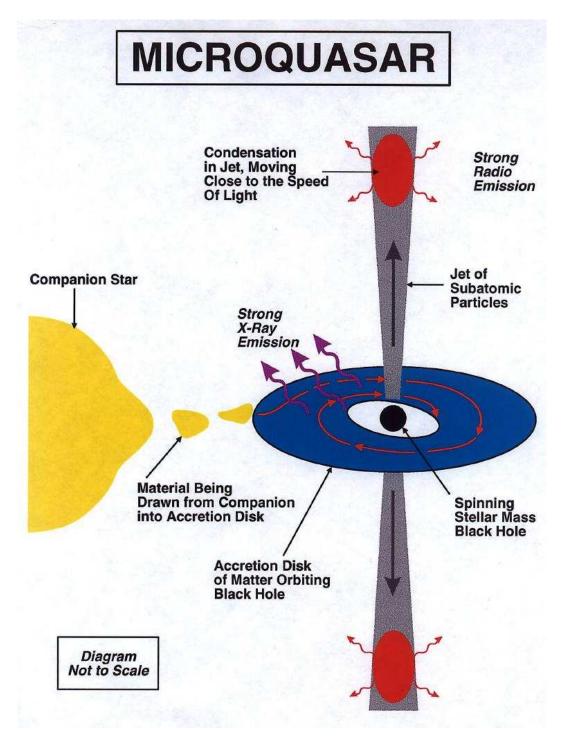


Fig. 1. This diagram illustrates current ideas of what may be microquasars. These are x-ray binary systems that eject plasma at relativistic speeds.

# SUPERLUMINAL MOTIONS

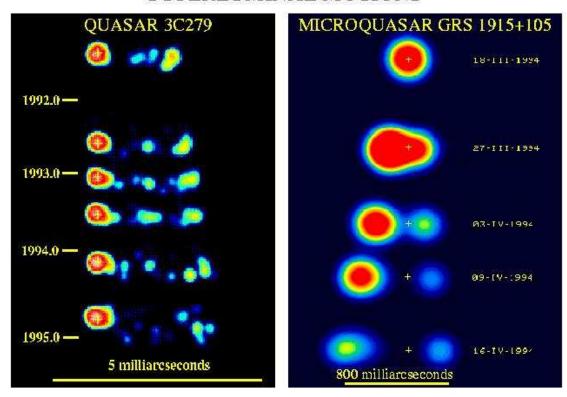


Fig. 2. Apparent superluminal motions observed in the microquasar GRS 1915+105 at 8.6  $\rm GHz^5$ ) and in the quasar 3C 279 at 22 GHz.

Galactic microquasar jets usually move in the plane of the sky  $\sim 10^3$  times faster than quasar jets and can be followed more easily than the later (see Figure 2). Because of their proximity, in microquasars two-sided jets can be observed, which together with the distance provides the necessary data to solve the system of equations, gaining insight on the actual speed of the ejecta. On the other hand, in AGN located at  $\leq 100$  Mpc, the jets can be imaged with resolutions of a few times the gravitational radius of the supermassive black hole, as was done for M 87.9) This is not presently possible in microquasars, since such a precision in terms of the gravitational radius of a stellar-mass black hole would require resolutions a few hundreds of kilometers. Then, in terms of the gravitational radius in AGN we may learn better how the jets are collimated close to the central engine. In summary, some aspects of the relativistic jet phenomena associated to accreting black holes are better observed in AGN, whereas others can be better studied in microquasars. Therefore, to gain insight into the physics of relativistic jets in the universe, synergy between knowledge of galactic and extragalactic black hole is needed.

### §3. Accretion-jet connection in microquasars and quasars

Microquasars have allowed to gain insight into the connection between accretion disk instabilities and the formation of jets. In  $\sim 1$  hour of simultaneous multiwavelength observations of GRS 1915+105 during the frequently observed 30-40 min x-ray oscillations in this source, the connection between sudden drops of the x-ray flux from the accretion disk and the onset of jets were observed in several ocassions<sup>10),11)</sup> (see Figure 3).

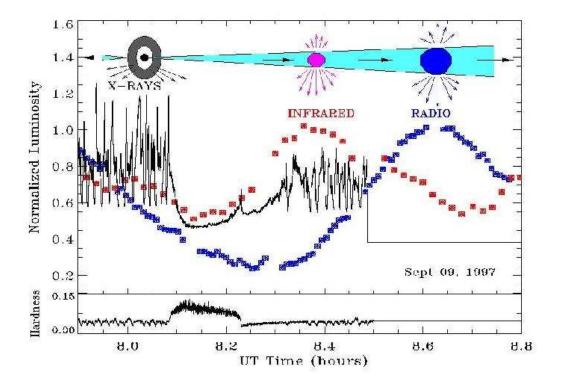


Fig. 3. Direct evidence for the disk-jet connection in the black hole x-ray binary GRS 1915+105.<sup>10</sup> When the hot inner accretion disk disappeared, its x-ray brightness abruptly diminished. The ensuing x-ray recovery documented the inner disk's replenishment, while the rising infrared and radio emission showed plasma being ejected in a jet-forming episode. The sequence of events shows that material indeed was transfered from the disk to the jets. Similar transitions have been observed in the quasar 3C 120,<sup>14</sup> but in time scales of years, rather than minutes.

From these observations we have learned the following:

- a) the jets appear after the drop of the x-ray flux,
- b) the jets are produced during the replenishment of the inner accretion disk,
- c) the jet injection is not instantaneous. It can last up to  $\sim 10$  min,
- d) the time delay between the jet flares at wavelengths of  $2\mu$ m, 2cm, 3.6cm, 6cm, and 21cm are consistent with the model of adiabatically expanding clouds that had been proposed to account for relativistic jets in AGN, <sup>12)</sup>

- e) synchrotron emission is observed up to infrared wavelengths and probably up to x-rays. This would imply the presence in the jets of electrons with TeV energies,
- f) VLBA images during this type of x-ray oscillations<sup>13)</sup> showed that the ejecta consist on compact collimated jets with lengths of  $\sim 100$  AU.
- g) there is a time delay of  $\sim 5$  min between the large drop of the x-ray flux from the accretion disk and the onset of the jets. These  $\sim 5$  minutes of silence suggest that the compact object in GRS 1915+105 has a space-time border, rather than a material border, namely, a horizon as expected in relativistic black holes. However, the absence of evidence of a material surface in these observations could have alternative explanations.

After the observation of this accretion disk-jet connection in a microquasar, an analogous connection was observed in the quasar 3C 120,<sup>14)</sup> but in scales of years rather than minutes. This time scale ratio is comparable to the mass ratio between the supermassive black hole in 3C 120 and the stellar black hole in GRS 1915+105, as expected in the context of the black hole analogy.

### §4. X-ray jets in AGN and microquasars

X-ray emission has been observed with Chandra and XMM-Newton in the radio jets, lobes and hot spots of quasars and radio galaxies. X-ray photons can be produced by inverse Compton scattering from the environment of the central engine up to distances of  $\sim 100$  kpc.<sup>15)</sup> Synchrotron x-ray radiation has been detected in some sources, most notably in the jet of M 87.

Steady, large-scale radio jets are associated to x-ray persistent microquasars.<sup>6)</sup> Extended x-ray emission associated to the radio emission was observed in the galactic source SS433/W50 up to distances of  $\sim 30$  pc from the central engine<sup>16)</sup> (see Figure 4). The x-rays extend in the same direction as the sub-arcsec, precessing jets. The jets in SS433 are hadronic, move with a velocity of 0.26c, and have a kinetic power of  $\sim 10^{39-40}$  erg s<sup>-1</sup>. Since no hot spots have been detected in the shock regions 30 pc away from the central engine, SS433/W50 cannot be considered a scale-down analog of a FR II radio galaxy. Most microquasars with extended jet emission have morphologies analogous to FR I's rather than FR II's radiogalaxies.

The recent discovery of radio<sup>17)</sup> and x-ray<sup>18)</sup> moving jets in microquasars rise the possibility of studying the formation of radio and x-ray lobes in real time. These observations show that jets may transport energy in a "dark" way, namely, in a way that is radiatively inefficient, until shocks are produced. Synchrotron x-ray emission from shocks at large distances from the central engines imply that microquasars are potential sources of cosmic rays and electrons with up to TeV energies.

### §5. Blazars and microblazars

The bulk Lorentz factors  $\Gamma$  in microquasars and quasars have similar values, and it had been proposed<sup>6)</sup> that microquasars with jet axis that form angles  $\leq 10^{\circ}$  with the line of sight should appear as "microblazars", showing analogous phenomena to blazars. Due to relativistic beaming, in microblazars the brightness of outbursts is

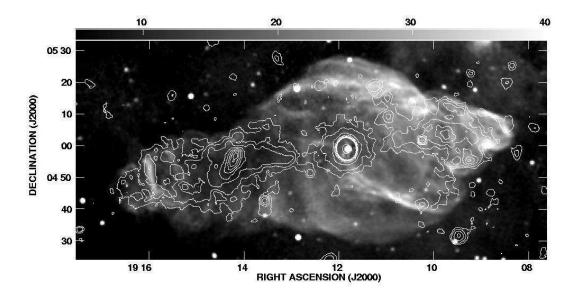


Fig. 4. VLA radio image at 1.5 GHz (grey scale) superimposed on the ROSAT x-ray contours of SS433/W50.<sup>16)</sup> The radio counterpart of the microquasar is the bright unresolved source at the center of the image. The lateral E-W extension of the nebula over  $\sim 1^{\circ}$  ( $\sim 50$  pc) is caused by the injection of relativistic jets from SS 433.

enhanced by factors of  $8 \times \Gamma^3$  and the interval of time of the phenomena is reduced by factors of  $1/2 \times \Gamma^{-2}$ . Then, microblazars should appear as intense sources of high energy photons with very fast variations of flux, which makes them difficult to find and to follow. Due to this difficulty and to the relatively low statistical probability of small angles between the jet axis and the line of sight,<sup>6)</sup> it is not surprising that most of the microquasars studied so far exhibit large angles ( $\geq 30^{\circ}$ ) between the jet axis and the line of sight.

It has been proposed that microblazars may be more frequently found in High Mass X-ray Binaries (HMXBs).<sup>19),20)</sup> In such binaries, gamma-rays can be produced by inverse Compton of the jet particles with the UV photons radiated by the massive donnor star. In fact, the three microquasars so far proposed as counterparts of variable EGRET unidentified sources are HMXBs with similar properties.<sup>21)</sup>

### §6. Extragalactic microquasars and super-Eddington x-ray sources

GRS 1915+105 and SS 433 may be the Milky Way counterparts of the two classes of most numerous super-Eddington x-ray sources found in external galaxies. GRS 1915+105 is a long lasting transient outburst x-ray binary with an evolved donnor of  $\sim 1~\rm M_{\odot}$ , whereas SS 433 is a persistent HMXB. SS 433 type of ULX's are preponderantly found in starburst galaxies like the Antennae, whereas luminous

x-ray sources of low mass as GRS 1915+105 may also be found in galaxies with a low rate of star formation.

Most of the ULX's would be stellar-mass black hole microquasars with the following possible properties:

- 1) HMXBs that host massive stellar black holes (M  $\geq 40~M_{\odot})$  with isotropic radiation.  $^{23)}$
- 2) HMXBs and LMXBs that host stellar black holes (M  $\sim 10~M_{\odot}$ ) with anisotropic radiation. <sup>22)</sup>
- 3) A few ( $\leq 1\%$ ) may be microquasars with relativistic boosted radiation. These should be very bright, highly time-variable, and have a hard x-ray/ $\gamma$ -ray photon spectrum.<sup>6)</sup>

Although less numerous, it is not exculded that some ULX's could be accreting black holes of intermediate-mass (100-1000  $M_{\odot}$ ).

### §7. X-ray/Radio correlations in low power black holes of all masses

Several teams of researchers are exploring interesting x-ray/radio correlations. Microquasars in the low-hard state exhibit radio/x-ray correlations.<sup>24)</sup> In the low-hard state the power output of quiescent black holes is jet-dominated and when the system moves to a high soft state the radio jets are quenched. The same seems to take place in AGN.<sup>25)</sup> A scheme to unify low-power accreting black holes has been proposed,<sup>26)</sup> where the black holes in Sgr A\*, LINERs, FR I, and BL Lac would be analogous to microquasar black holes in the low-hard state.

Following studies<sup>27)</sup> of correlations between radio and bolometric luminosities, a fundamental plane of black hole activity in terms of the black hole mass and x-ray and radio core luminosities is proposed.<sup>28)</sup> This correlation holds for radiatively inefficient accretion, not for bright thin synchrotron emitting states.

At present, these empirical correlations have large scatters. However, if they became more robust, the mass of black holes could be inferred from the x-ray and radio fluxes, independently of theoretical models.

#### §8. Time variations of flux and the masses of black holes

Time variations of flux may be correlated with the mass of the black hole.

- 1) The duration of the x-ray flares observed in stellar-mass black holes and in Sgr A\* seem to be proportional to the mass of the black holes. In Cygnus X-1 and other x-ray black hole binaries, flares with durations of 1-10 ms are observed.<sup>29)</sup> On the other hand in Sgr A\*, x-ray flares lasting 400-10,000 sec have been observed with Chandra<sup>30)</sup> and XMM-Newton.<sup>31)</sup> As expected, the time ratios of the power variabilities are comparable to the black hole mass ratios.
- 2) For a given black hole spin, the maximum frequencies of quasi periodic oscillations (QPOs) of flux are expected to be proportional to the mass of the black hole. In 4 microquasars, 3:2 twin peak x-ray QPOs of maximum frequency in the range of 100-500 Hz have been observed, from which angular momenta  $a = J/(GM/c^2) = 0.6$ -0.9 have been derived.<sup>32)</sup> On the other hand, 17 min infrared QPOs have

been reported in Sgr A\*, from which it has been inferred an angular momentum  $a = 0.52.^{33}$ ) As expected, these QPOs appear to scale with the mass of the black hole. If the 17 min QPO in Sgr A\* is confirmed as a component of a twin peak fix QPO of maximum frequency, this correlation could be used to derive black hole masses, and in particular, those of the super-Eddington x-ray sources in external galaxies.<sup>32)</sup>

3) Some properties of the aperiodic variability (noise) in AGN and x-ray binaries seem to be correlated with the mass of the compact objects. The break time scale in the power spectra density of black holes seems to scale linearly with the mass of the black hole.<sup>34)</sup> The broad band break time in the Sey 1 NGC 3516 scales linearly with that of Cyg X-1 in the low-hard state.<sup>35)</sup> If this type of correlation is confirmed it could also be used to estimate the mass of black holes in extragalactic super-Eddington x-ray sources.

### §9. Relativistic iron lines in stellar and supermassive black holes

AGN frequently exhibit broad iron  $K\alpha$  lines skewed to low energies.<sup>36)</sup> The shape of these lines is consistent with emission from the surface of an accretion disk extending from about 6 to more than 40 gravitational radii. Occasionally the red wing of the line extends below 4 keV and the current explanation is that the disk extends within 6 gravitational radii implying that the black hole is rapidly spinning. Now it is widely believed that this spectral feature is a probe of the immediate environment of black holes.<sup>37)</sup> Until recently, only smeared edges with little evidence for line emission had been observed in Galactic black hole binaries. But after Chandra, XMM-Newton and Beppo-SAX, similar emission iron lines to those in AGN were found, even in the ASCA archive.<sup>38)</sup>

Besides emission lines skewed to low energies, analogous spectra to AGN-like warm absorbers are observed in some x-ray binaries.<sup>39)</sup> The absorption is variable and it is believed to be produced in a dense local disk wind rather than in the ISM. A finding possibly related to these absorption lines is the discovery with INTEGRAL of black hole binaries with strong x-ray absorption, much larger than that derived from optical and infrared observations, which also implies that the absorption is local rather than in the ISM.

The iron line in stellar black hole binaries can be used to investigate:

- 1) the physical models of the  $K_{\alpha}$  line. Because of the short dynamical time scales, the shape of the line can be correlated with the x-ray state of the accretion disk, and corona-disk interactions.
- 2) the dense plasma outflows from accreting black holes. The study of warm absorber lines similar to those seen in Seyferts may be important to estimate the mass outflows in x-ray binaries.
- 3) the spin of the accreting black hole. This is important to test models where the jets are powered by the spin of the black hole.

At present, the main constrain to derive the slope of the iron lines is due to the uncertainties on the shape of the continuum at energies  $\geq 8$  keV.

### §10. Microquasars as fossils of gamma-ray burst sources

Gamma-ray bursts (GRBs) of long duration are believed to be jets from collapsars at cosmic distances. In this context there should be astrophysical and physical connections between GRB sources and microquasars. If GRB sources are microquasars in formation at cosmic distances, microquasars in our galaxy should contain clues on the physics in collapsars.

It is believed that collapsars that produce GRBs take place in close massive binaries because:

- 1) the core must be spun up by spin-orbit interaction in order to provide enough power to the jet that drills the collapsing star all the way from the core up to the external layers.<sup>40)</sup>
- 2) GRBs seem to be associated to SNe Ic. This is the class of SNe that do not show H and He lines, implying that before the explosion the progenitor of those GRBs had lost the H and He layers. These layers are more easily lost if the progenitor was part of a massive binary that underwent a common envelope phase. Furthermore, SNe Ic exhibit 4-7 % polarization, which are an indication of asymmetric explosions caused by collimated jets.

As for AGN, it has been proposed<sup>41),42)</sup> an unification scheme where GRBs, x-ray flashes and SNe Ic are the same phenomenon, but viewed from different angles. However, radio observations of SNe Ic suggest<sup>43)</sup> that the characteristics of supernovae are not dictated by the viewing angle but rather by the properties of the central engine. The observed variety of cosmic explosions (GRBs, x-ray flashes, SNe Ic) would then be explained by the varying fraction of the explosion energy that is channeled into relativistic ejecta.

### §11. Constrains on collapsar physics from microquasar kinematics

It is believed that stellar black holes can be formed in two different ways: Either the massive star collapses directly into a black hole without a supernova explosion, or an explosion occurs in a protoneutron star, but the energy is too low to completely unbind the stellar envelope, and a large fraction of it falls back onto the short-lived neutron star, leading to the delayed formation of a black hole. If the collapsar takes place in a binary that remains bound, and the core collapse produced an energetic supernova, it will impart the center of mass of the system with a runaway velocity, no matter the explosion being symmetric or asymmetric. Therefore, the kinematics of microquasars can be used to constrain theoretical models of the explosion of massive stars that form black holes.

Recently, the runaway velocities of several microquasars have been determined. 45)-47) Although the number statistics is still rather low, the preliminary results are consistent with evolutionary models for binary massive stars, 44) where neutron stars and low-mass black holes form in energetic supernova explosions, whereas black holes with the larger masses form silently.

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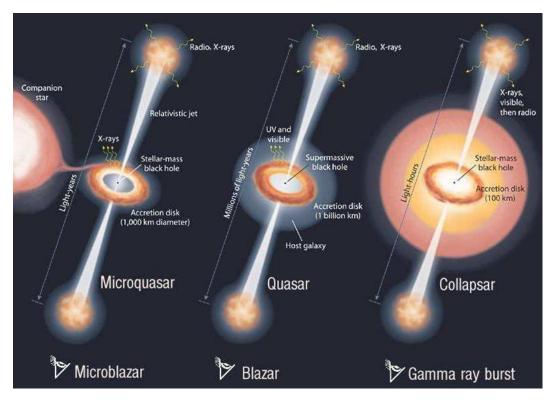


Fig. 5. A unique universal mechanism may be responsible for three types of astronomical objects: microquasars (left); quasars (center); and collapsars (right), the massive, suddenly collapsing stars believed to cause some gamma-ray bursts. Each contains a black hole (probably spinning), an accretion disk (which transfers material to the black holes), and relativistic jets (which emerge from a region just outside the black holes, carrung away angular momentum). Microquasars and quasars can eject matter many times, while collapsars form jets but once. When the jet is aligned with an observer's line of sight these objects appear as microblazars, blazars, and gamma-ray bursters, respectively. The components of each panel are not drawn to scale); scale bars denote jet lengths. (Sky & Telescope, May 2002, 32)

### §12. Relativistic jets in AGN, microquasars and GRB sources

It was suggested that irrespective of their mass there may be a unique universal mechanism for relativistic jets in accreting black holes<sup>48</sup> (see Figure 5). Although in AGN, microquasars and GRB sources there are different physical conditions, it was proposed that all jets are produced by an unique electromagnetic mechanism, in which charged plasma is accelerated by electric fields that are generated by a rotating magnetic field (Meier, astro-ph/0312047). However, the most popular GRB jet models at this time are baryon dominated, and the factors that control the jet power, collimation and speed, remain unknown.

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